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THE STATUS OF MOLECULES [1]

T.Barnes
Physics Division and Center for Computationally Intensive Physics
Oak Ridge National Laboratory, Oak Ridge, TN 37831
and
Department of Physics and Astronomy
University of Tennessee
Knoxville, TN 37996

Abstract

This report summarizes the experimental and theoretical status of hadronic molecules, which are weakly-bound states of two or more hadrons. We begin with a brief history of the subject and discuss a few good candidates, and then abstract some signatures for molecules which may be of interest in the classification of possible molecule states. Next we argue that a more general understanding of $2 \to 2$ hadron-hadron scattering amplitudes will be crucial for molecule searches, and discuss some of our recent work in this area. We conclude with a discussion of a few more recent molecule candidates (notably the $f_0(1710)$) which are not well established as molecules but satisfy some of the expected signatures.

1 Brief History

In the 1970s it was widely believed that there would be a very rich spectrum of discrete levels of multiquark resonances. The argument was that the many known $q\bar{q}$ and qqq resonances exist because they are color singlets, so we should expect other color-singlet sectors of Hilbert space to possess resonances as well. The "four-quark" $q^2\bar{q}^2$ system was the subject of many detailed studies because it contains the first color-singlet multiquark system beyond three quarks, and because this system could couple to baryon-antibaryon systems through a single $q\bar{q}$ annihilation. Partly for this reason $q^2\bar{q}^2$ states were referred to as "baryonia". Although there were many reports of possible experimental baryonium states, and many detailed spectra were published in various models, no such states have yet been established. In sectors which support $q\bar{q}$ states the spectrum is already very complicated, so the issue of multiquark states remains somewhat obscure. However when one specializes to "smoking gun" systems such as the exotic I=2 channel, which is predicted to support a light 0^{++} $q^2\bar{q}^2$ level (at about 1.2 GeV in the MIT bag model) but cannot have a $q\bar{q}$ state, there is no resonance in evidence [1].

The problems with the various theoretical models that led to erroneous predictions of discrete multiquark levels have been discussed by Isgur [2]. The novel feature of multiquark systems which the models missed is that, unlike $q\bar{q}$ and qqq, they need not exist as single color-singlet hadronic clusters; a $q^2\bar{q}^2$ system in general has some projection onto two color-singlet $q\bar{q}$ mesons, and continuous deformation into two separate mesons appears to be energetically favored in most cases. This rearrangement into color singlets is called "fall-apart" [3], and apparently excludes most single-hadron $q^2\bar{q}^2$ clusters as resonances. Fall-apart would not be possible if the cluster had a mass lower than the threshold of the two-hadron system it can rearrange into, which is why the question of the existence of multiquark clusters such as the

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H $u^2d^2s^2$ system is so interesting. The bag model predicts this state 81 MeV below $\Lambda\Lambda$ threshold [3], but this prediction should be treated with caution because the bag model has previously given a misleading picture of multiquark states. The tentative evidence for dilambda hypernuclei [4] (if confirmed) makes the existence of an H six-quark resonance well below $\Lambda\Lambda$ threshold appear very unlikely. Whether single multiquark clusters exist as resonances under any conditions is a detailed dynamical question, which should be investigated using models that allow the system itself freedom to choose between a single cluster or separate color singlets. At present it appears that single $q^2\bar{q}^2$ hadronic clusters may only exist as resonances in heavy-light systems such as $c^2\bar{q}^2$ [5].

It was the lack of sufficient freedom in the wavefunctions that led to the spurious prediction of many discrete baryonium levels; the models *assumed* that such states existed, and then gave predictions for the spectrum of these discrete levels. The first detailed study that allowed the $q^2\bar{q}^2$ system to choose between clusters and separate mesons as ground states was the variational study of the 0^{++} sector by Weinstein and Isgur [6], which found that continuous deformation of a cluster into separate $q\bar{q}$ mesons was usually preferred energetically. The two exceptions found by Weinstein and Isgur will be discussed below.

2 A Few Good Candidates

2.1) Nuclei

Lest one form the impression that hadronic molecules are controversial, note that the $\sim 10^5$ known nuclear levels are all hadronic molecules. Of course the term is usually applied to hadron pairs; even if we specialize to this restricted case, the deuteron can be cited as a noncontroversial example of a dominantly S-wave hadronic molecule. Its almost-bound I=1, S=0 partner is an example of another phenomenon which may appear elsewhere in the spectrum, a molecular resonance above threshold which is due to a strongly attractive final-state interaction. The existence of so many nuclear species is especially notable since the nucleon-nucleon system is rather unfavorable for the formation of bound states, due to the strong short-distance repulsive core. This suggests that many other families of bound hadrons may exist, although they may not be experimentally accessible except in special cases.

2.2) $\Lambda(1405)$

In meson-baryon sectors, the $\frac{1}{2}^-$ $\Lambda(1405)$ has long been considered a candidate $\bar{K}N$ bound state [7], since it is just below the $\bar{K}N$ threshold, has S-wave $\bar{K}N$ quantum numbers, and is nearly 150 MeV below the mass expected for the lightest $\frac{1}{2}^-$ Λ^* baryon in the quark model [8]. (The decay amplitudes however are consistent with a uds assignment [8].) Theoretical study of this channel has been incomplete, however, because of the complications of open channels and $q\bar{q}$ annihilation; a model which includes mixing in the full $N\bar{K}$-$\Sigma\pi$-uds system is required for a complete study of this state. The radiative partial widths to $\gamma\Lambda$ and $\gamma\Sigma^0$ compared to quark model predictions for a uds baryon may allow a convincing test of the molecule assignment. A wide range of theoretical numbers has been reported for these radiative widths [9], so one should be careful to use techniques which give reliable results for well-established qqq quark model states.

2.3) $f_0(975)$ and $a_0(980)$

Weinstein and Isgur [6] found an exception to the fall-apart phenomenon in the scalar sector, with parameters corresponding to the $qs\bar{q}\bar{s}$ system. Here weakly-bound deuteronlike states of kaon and antikaon were found to be the ground states of the four-quark system; Weinstein and Isgur refer to these as "K$\bar{\text{K}}$ molecules". The scalars $f_0(975)$ and $a_0(980)$ were obvious candidates for these states, having masses just

below $K\bar{K}$ threshold and strong couplings to strange final states. Subsequently the $\gamma\gamma$ couplings of the $f_0(975)$ and $a_0(980)$ were found to be anomalously small relative to expectations for light $^3P_0$ $q\bar{q}$ states ($q = u, d$), as discussed in Refs. ([10, 11]). The status of the $K\bar{K}$ molecule assignment and the many points of evidence in its favor have been discussed recently by Weinstein and Isgur [12, 13].

Although Morgan and Pennington have argued against a molecule interpretation of the $f_0(975)$ [14], their criticism applies to a $K\bar{K}$ potential model in which the $f_0(975)$ is a single pole in the scattering amplitude. The more recent work of Weinstein and Isgur [12, 13] incorporates couplings to open meson-meson channels and heavier $^3P_0$ $q\bar{q}$ states, and although the f_0 and a_0 states remain dominantly $K\bar{K}$, these modifications may answer the objections of Morgan and Pennington. Pennington suggests that the term "deuteronlike" may be a misnomer, if couplings to other states than $K\bar{K}$ play an important rôle in these states [10]. Thus it appears that the important question regarding the f_0 and a_0 may be one of detail, specifically how large the subdominant non-$K\bar{K}$ components are in these states and how they can be observed experimentally.

Finally, Gribov and collaborators [15] have discussed the possibility that the $f_0(975)$ and $a_0(980)$ might be novel $q\bar{q}$ states constructed of negative-energy Dirac levels, which they expect might have small length scales of ~ 0.2 fm and mass scales of ~ 1 GeV. They note that this suggestion can also be tested by an accurate determination of the $\gamma\gamma$ partial widths of these states.

3 Signatures for Molecules

Leaving aside questions of detailed dynamics, there are several obvious signatures for hadron-pair molecules that may be abstracted from these candidates. These signatures are:

1) J^{PC} **and flavor quantum numbers of an L=0 hadron pair.**

The residual "nuclear" strong forces that bind molecules are of such short range that L>0 molecules appear unlikely in light hadronic systems. Actually there is a possible exception, the $\psi(4040)$, which couples so strongly to $D^*\bar{D}^*$ that it was suggested as a P-wave $D^*\bar{D}^*$ molecule (note $E_B \approx 0$) some time ago [16]. This exception may be possible because heavier mesons bind more easily, and the light quarks insure relatively strong interactions between them. Should this state actually be a P-wave charmed-meson molecule, a spectrum of more deeply-bound S-wave charm molecules is anticipated [17].

2) **A binding energy of at most about** $50 - 100$ **MeV.**

From the uncertainty principle; a minimum separation of ≈ 1 fm is required for hadrons to maintain separate identities, which gives $E_B \sim 1/(2\mu R^2) \sim 1/(1 \text{ GeV}) \cdot (1 \text{ fm})^2 \approx 50$ MeV, and of course a factor-of-two uncertainty is plausible in this simple estimate. For comparison, Weinstein and Isgur find an rms $K\bar{K}$ separation of about 1.7 fm in their model of the $f_0(975)$ and $a_0(980)$, which have $E_B \approx 10 - 20$ MeV. Note also that an attractive interaction may lead to a final-state enhancement in S-wave just *above* threshold, which may or may not be resonant; the I=1, S=0 partner of the deuteron is an example of such a resonance, and the $f_1(1420)$ may be an example of a nonresonant final-state enhancement.

3) **Strong couplings to constituent channels.**

As an example, the anomalously large coupling of the $f_0(975)$ to $K\bar{K}$, as indicated by $B(K\bar{K})/B(\pi\pi) \approx 1/4$ despite the near absence of $K\bar{K}$ phase space, is an important clue that it is not a nonstrange $q\bar{q}$ state.

4) **Anomalous EM couplings relative to expectations for conventional quark model states.**

The $f_0(975)$ for example has a tiny $\gamma\gamma$ partial width of perhaps 0.2 Kev to 0.6 Kev (depending on the analysis) [10]. This small $\gamma\gamma$ width is expected for a $K\bar{K}$ molecule [11], but for a nonstrange $^3P_0$ $q\bar{q}$ state the quark model predicts about 3 Kev [18], as has recently been found for the broad $f_0(\approx 1300)$ [19]. Close, Isgur and Kumano [20] suggest a related test for the $f_0(975)$ and $a_0(980)$ involving the radiative decays $\phi \to \gamma(f_0, a_0)$, which may be possible at DAΦNE and CEBAF.

4 Back to Basics: $2 \to 2$ Scattering Amplitudes

Low-energy $2 \to 2$ hadron scattering is interesting in itself as a nontrivial aspect of QCD, and if we can reach an understanding of the important scattering mechanisms in terms of quarks and gluons, we should be able to predict which channels experience strong attractive forces and hence may support molecular bound states.

Hadron-hadron scattering amplitudes at low energies are generally thought to involve the quark-gluon interaction nonperturbatively, so although calculations of meson-meson and baryon-baryon interactions at the quark-gluon level have been rather successful, they have typically used complicated nonperturbative methods such as resonating group or variational techniques. Extension of this work to channels such as vector-vector has been slow largely because of the difficulty of applying these methods, although some variational and Monte Carlo results have been reported for special cases, including an extension of the Weinstein-Isgur work to I=2 $\rho\rho$ [21].

Recently our collaboration has found evidence that the Ps-Ps scattering amplitudes found by Weinstein and Isgur (in channels without $q\bar{q}$ annihilation) are actually dominated by perturbative diagrams, although "higher-twist" contributions in the form of external $q\bar{q}$ wavefunctions attached to the diagrams are an essential, nonperturbative aspect of the scattering amplitudes [22, 23]. We initially studied I=2 $\pi\pi$ [22] and I=3/2 $K\pi$ [24] and found that OGE followed by constituent interchange dominates these scattering amplitudes, and leads to results which are numerically very similar to the Ps-Ps potentials found variationally by Weinstein and Isgur. Recent lattice QCD results for the I=2 $\pi\pi$ scattering length support our conclusion regarding the dominance of these diagrams [25]. We refer to these perturbative diagrams with external wavefunctions attached as "quark Born diagrams". With SHO quark model wavefunctions these lead to overlap integrals that can often be evaluated in closed form, and the results for $\pi\pi$ and $K\pi$ S-wave phase shifts are in excellent agreement with experiment over the entire range of energies studied given standard quark model parameters. We have similarly found good agreement in the I=0 and I=1 KN system [26] (*albeit* with some problems at higher energies which may be due to the assumption of single-Gaussian nucleon wavefunctions). In our study of NN, NΔ and ΔΔ [27] we found the strongest diagonal attraction in the $I = 0, S = 1$ ΔΔ channel, in agreement with the variational work of Maltman [28]. Very recently we have studied the $N_s = 2$ baryon-baryon channel [29], and we agree with Oka, Shimizu and Yazaki and Straub *et al.* [30] that quark model forces lead to a repulsive ΛΛ core interaction; of the six $N_s = 2$ octet-octet channels we find that only I=0,S=0 ΣΣ has an attractive core. It is reassuring that exactly the same conclusion was reached by Oka *et al.* using nonperturbative resonating group methods.

Given this reasonably successful description of hadron-hadron scattering at low energies, can we proceed to study all experimentally accessible channels and see in which we expect hadronic molecules to form? Unfortunately this is not yet possible. The difficulty is that $q\bar{q}$ annihilation appears to be the dominant effect when allowed (as in I=0,1 $\pi\pi$ and I=1/2 $K\pi$), so a realistic description of scattering amplitudes in these channels requires accurate modelling of the couplings of different sectors of Hilbert space (as in $\pi\pi \to f_0(q\bar{q}) \to \pi\pi$). On closer examination of the Weinstein-Isgur results [13] it now appears

that both level repulsion against higher-mass s-channel $q\bar{q}$ resonances and nonresonant scattering are needed to bind both the I=0 and I=1 $K\bar{K}$ systems. Without level repulsion against the $q\bar{q}$ $^3P_0$ states at $\approx$ 1.3 GeV only the I=0 molecule binds. The existence of molecules in some channels may be due entirely to level repulsion against a more massive quark model state, and the hadronic couplings of most quark-model states are not well enough established to model this level repulsion accurately. Remarkably, the $q\bar{q}$ pair production process is still rather poorly understood (for a recent study see [31]), and is usually treated using phenomenological models such as $^3P_0$ that have no clear relation to QCD. Accurate modelling of hadronic forces in channels with annihilation, and hence reliable predictions of molecules, must await a better understanding of the $q\bar{q}$ annihilation mechanism.

5 A Few More Candidates

There are many resonances above 1.4 GeV which may prove to be molecular states. Here I will discuss three such I=0 resonances which do not appear to have a natural assignment as $q\bar{q}$ mesons, and which merit consideration as molecule candidates. These are the "$\theta(1720)$" (now known as the $f_0(1710)$), the $AX(1515)$ (originally reported by ASTERIX $P\bar{P} \to \pi^+\pi^-\pi^0$ [32], now believed to be dominantly J=0 and called the $f_0(1520)$ [34]), and the $f_1(1420)$. For completeness I conclude with a reminder of other sectors of Hilbert space which may possess molecular resonances.

5.1) $f_0(1710)$

Early references often considered this a glueball candidate, since it was discovered in a ψ radiative decay [35] and has no obvious assignment in the $q\bar{q}$ spectrum. It was also discussed as a possible $qs\bar{q}\bar{s}$ multiquark state (a single cluster rather than a molecule), although the presence of a fall-apart coupling to $K\bar{K}$ makes this appear untenable. The $f_0(1710)$ appears unlikely to be a radially excited nonstrange $^3P_0$ $q\bar{q}$ because it has a mass 110 MeV below the Godfrey-Isgur prediction [36] and it has a very weak coupling to $\pi\pi$ final states, which makes both nonstrange $q\bar{q}$ and glueball assignments rather implausible (assuming naive flavor-singlet glueball couplings).

We consider the $f_0(1710)$ a strong vector-molecule candidate. There have been several suggestions in the literature regarding molecule assignment for this state, which differ primarily in the proposed binding mechanism; this leads to observable differences in the predicted decay modes.

Törnqvist [37] suggests a $K^*\bar{K}^*$ assignment for this state. If the K^*s decay as free hadrons this leads one to expect a large partial width of $\Gamma(f_0(1710) \to K^*\bar{K}^*) \approx 2\,\Gamma(K^*) \approx 100$ MeV, making it the dominant decay mode, since the 1992 PDG gives the $f_0(1710)$ a total width of 146 ± 12 MeV. This prediction appears to disagree with the branching fractions to other final states estimated by the PDG. Ericson and Karl [38] have studied the one-pion-exchange binding mechanism proposed by Törnqvist, and conclude that it may just provide sufficient attraction to bind $K^*\bar{K}^*$. They also conclude that this mechanism would predict several other vector-vector and meson-baryon molecules, such as B^*B^* and $N\Sigma$.

Dooley, Swanson and Barnes [39] assumed that a different mechanism was responsible for the dominant vector-vector interactions, specifically a OGE constituent interchange model which they had previously applied to several other channels (see previous section). This model predicts a very strong coupling between $K^*\bar{K}^*$ and $\omega\phi$ channels, found by Swanson [23] and represented using off-diagonal hadron-hadron potentials. Dooley *et al.* used these potentials in a multichannel generalization of the Weinstein-Isgur work, and found weakly bound molecules in several vector-vector systems. In the I=0 $qs\bar{q}\bar{s}$ sector they found a linear combination of two-meson basis states as a 0^{++} ground state,

$$|\Psi_0(qs\bar{q}\bar{s}\ 0^{++})\rangle = \frac{1}{\sqrt{2}}\Big(|K^*\bar{K}^*\rangle + |\omega\phi\rangle\Big)\ , \tag{1}$$

and a 2^{++} excited state somewhat higher in mass. This linear combination predicts $K\bar{K}$ and $\eta\eta$ branching fractions close to experimental values [40] and also gives reasonable results for the flavor-tagging $\psi \to VX$ hadronic decays, which suggest that the $f_0(1710)$ couples as if it were a strange-nonstrange mixed-flavor state. (A similar result is known for the $f_0(975)$ in these decays.) A $K^*\bar{K}^*$ decay mode is expected as in the pure $K^*\bar{K}^*$-molecule picture, but with a smaller branching fraction of about 35%. The branching fraction of a $(K^*\bar{K}^* + \omega\phi)/\sqrt{2}$ molecule to $\pi\pi$ is more problematical; Dooley has recently found it to be about 5% [40], consistent with experiment. A very characteristic electromagnetic decay mode in this assignment is $f_0(1710) \to \phi\pi^0\gamma$, with a branching fraction of 0.3%, due to constituent-ω radiative decay. It should also have an anomalously small $\gamma\gamma$ coupling relative to a nonstrange I=0 $q\bar{q}$ state such as the $f_2(1274)$ [41].

A search for a $K^*\bar{K}^*$ mode is clearly the most important test of the vector-molecule models of the $f_0(1710)$, since both models expect a large $K^*\bar{K}^*$ branching fraction. Of course one $K\pi$ combination will be skewed downwards from the free K^* mass by slightly more than E_B, assuming that this acts as a sequential decay, $f_0(1710) \to K^*(\bar{K}\pi)$ followed by decay of the free recoiling K^*.

5.2) $f_0(1520)$

This state, like the $f_0(1710)$, has a complicated history in which it was originally attributed to a 2^{++} resonance [32, 33], with subsequent analysis changing it to 0^{++} with a small additional 2^{++} amplitude [34]. The recent Crystal Barrel study of the reactions $P\bar{P} \to \pi^o\pi^o\pi^o$ and $P\bar{P} \to \eta\eta\pi^o$ finds two broad scalar states, an $f_0(1365)$ with a mass and width of $M = 1365^{+20}_{-55}$ MeV and $\Gamma = 268 \pm 70$ MeV (which appears consistent with expectations for a ${}^3P_0$ $q\bar{q}$ state) and the $f_0(1520)$, with a mass and width of $M = 1520 \pm 25$ MeV and $\Gamma = 148^{+20}_{-25}$ MeV. The mass of the $f_0(1520)$ rules out any quarkonium assignments except $s\bar{s}$, but its couplings are inconsistent with $s\bar{s}$; it has been reported in $\pi\pi$, $\eta\eta$ [34], and $\eta\eta'$ final states [42], with amplitudes approximately consistent with flavor-singlet couplings.

The reported couplings of the $f_0(1520)$ make it a plausible glueball candidate, as does its mass; recent lattice gauge theory expectations for the lightest glueball are that it should be a scalar with a mass of about 1.5 GeV [43]. Of course this prediction uses the quenched approximation, but this leads to quite reasonable results for the spectrum of conventional light $q\bar{q}$ mesons. A crucial test of the glueball assignment will be a measurement of the branching fraction to $K\bar{K}$; if this is also consistent with a flavor singlet, then a strong case for the identification of the $f_0(1520)$ with the light scalar glueball can be made.

If the $f_0(1520)$ is found to couple only weakly to $K\bar{K}$, another possibility is that it is a vector meson molecule. Since the $\rho\rho$ and $\omega\omega$ thresholds are not far above this state and it has S-wave $\rho\rho$ and $\omega\omega$ quantum numbers, it is an obvious candidate for a vector-vector molecule. A possible $\rho\rho$ assignment has been suggested by both Kalashnikova [45] and Törnqvist [37]. A pure $\rho\rho$ bound state however appears inconsistent with the new Crystal Barrel width, since a weakly bound $\rho\rho$ state would have a width due to constituent decay of

$$\Gamma(\rho\rho) \approx 2\,\Gamma(\rho) \approx 300 \text{ MeV} . \tag{2}$$

Another possibility is that strong mixing between the nearly degenerate $|\rho\rho\rangle$ and $|\omega\omega\rangle$ basis states has led to a coherent superposition close to

$$|VV\rangle = \frac{1}{\sqrt{2}}\Big(|\rho\rho\rangle + |\omega\omega\rangle\Big) ; \tag{3}$$

with this linear combination one would expect a strong width from constituent decays alone of

$$\Gamma(VV) \approx \Gamma(\rho) + \Gamma(\omega) \approx 160 \text{ MeV} , \tag{4}$$

consistent with the reported total width of the $f_0(1520)$. This $(\rho\rho + \omega\omega)/\sqrt{2}$ model also makes several other characteristic predictions, such as the dominance of $\rho\rho$ decays, $B(\omega\omega)/B(\rho\rho) \approx 1/20$ and $\Gamma(f_0(1520) \to \omega\pi^0\gamma) \approx 0.8$ MeV (both from consideration of constituent decays).

The possibility of nonstrange vector-vector molecules may have independent support from the Crystal Barrel collaboration [44], who report evidence for a $\rho\rho$ enhancement with a mass and width of $M = 1374 \pm 38$ MeV and $\Gamma = 375 \pm 61$ MeV. These values are inconsistent with the $f_0(1520)$ alone, and might be due to the $f_0(1365)$, to a combination of the $f_0(1365)$ and $f_0(1520)$, or even to a third broad f_0.

5.3) $f_1(1420)$

The final unusual meson state we consider is the $f_1(1420)$, which is a candidate for a nonresonant threshold enhancement ($K^*\bar{K}+h.c.$) rather than a molecular bound state. This possibility was suggested by Caldwell [46], and satisfies the criteria of lying just above the $K^*\bar{K}$ threshold and having quantum numbers allowed for that pair in S-wave. The apparent width of the enhancement should not be narrower than the intrinsic width of the K^*, and indeed the PDG values are similar, $\Gamma(f_1(1420)) = 56 \pm 3$ MeV and $\Gamma(K^*) = 50$ MeV. Longacre [47] found that a model with an S-wave nonresonant ($K^*\bar{K} + h.c.$) enhancement gives a good description of this state, and Isgur, Swanson and Weinstein [48] also favor this possibility. The (off-shell) $\gamma\gamma^*$ couplings of the $f_1(1420)$ relative to expectations for a 1^{++} $s\bar{s}$ state may provide a test of the hadron-pair model.

5.4) Z^*s and dibaryons

We conclude this section with a reminder that there may be hadronic molecules in other sectors of Hilbert space, which have received little recent attention because they do not correspond to $q\bar{q}$ or qqq flavor states in the quark model or because of the lack of appropriate experimental facilities.

One especially interesting system, which should soon be accessible to experiments at DAΦNE and perhaps CEBAF, is the kaon-nucleon system. Possible resonances in the $q^4\bar{s}$ sector are known as Z^*s, and although there have been indications of such states for many years in elastic KN scattering [49], the lack of clear evidence for multiquark states and the uncertainties of partial wave analyses in the KN system have left the possibility of such states a controversial question. In our recent theoretical study of KN, K^*N, $K\Delta$ and $K^*\Delta$ systems [26] we found that several of these channels, notably the minimum-total-spin, minimum-total-isospin ones, have strongly attractive interactions. The experimental reports of Z^* resonances may represent observations of final state enhancements or even of meson-baryon bound states just below threshold. Clarification of this issue will require accurate partial wave analyses of KN scattering, and data on the inelastic channels $KN \to K^*N, K\Delta$ and $K^*\Delta$ would also be very valuable for the study of possible Z^* states. Here the theoretical calculations should be more reliable since these reactions are annihilation-free at valence quark level.

Finally, there are controversial reports of resonances in partial wave analyses of elastic NN scattering [50], and these "dibaryon" resonances may also include S-wave baryon-baryon molecule states. This system too is relatively straightforward theoretically because it is annihilation-free, and a few $\Delta\Delta$ channels (notably I=0,S=1, I=1,S=0, I=0,S=3 and I=3,S=0) have been cited by theorists as the most likely for the formation of nonstrange baryon-baryon resonances [27, 28].

6 Summary and Conclusions

The hadronic spectrum exhibits many quasinuclear hadron bound states, which have become known as "molecules". In this talk we discussed the status of several of these candidate hadronic molecules, including nuclei (which are nucleon molecules), the $\Lambda(1405)$, the mesons $f_0(975), a_0(980), f_0(1710), f_0(1520)$ and $f_1(1420)$, Z^*s and dibaryons.

The study of molecules is a subtopic of the problem of determining $2 \to 2$ hadron-hadron scattering amplitudes near threshold. Although this is widely held to be a nonperturbative problem, our collabora-

tion has found that a simple class of perturbative diagrams (with external quark wavefunctions attached) dominates low-energy scattering in annihilation free channels. We refer to these diagrams as quark Born diagrams; their study has led us to predictions of several channels which may support hadronic molecules. One such state is the $f_0(1710)$, which we believe may be a vector-vector $(K^*\bar{K}^* + \omega\phi)/\sqrt{2}$ molecule; this assignment leads to detailed predictions of couplings and decay modes.

The study of molecules would be greatly assisted by a better understanding of hadron scattering mechanisms at the quark and gluon level. For this reason we particularly advocate future studies of scattering amplitudes in channels such as KN, in which one can study nonresonant two-body scattering in the absence of complications due to valence $q\bar{q}$ annihilation.

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